Measurement of the Lifetime and Separation Energy of 3H

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Editors' Suggestion **Featured in Physics**

Measurement of the Lifetime and Λ Separation Energy of ${}^{3}_{\Lambda}\mathrm{H}$

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(ALICE Collaboration)

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The most precise measurements to date of the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime τ and Λ separation energy B_{Λ} are obtained using the data sample of Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV collected by ALICE at the LHC. The ${}^{3}_{\Lambda}\mathrm{H}$ is reconstructed via its charged two-body mesonic decay channel (${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ and the charge-conjugate process). The measured values $\tau = [253 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst})]$ ps and $\mathrm{B}_{\Lambda} = [102 \pm 63(\mathrm{stat}) \pm 67(\mathrm{syst})]$ keV are compatible with predictions from effective field theories and confirm that the ${}^{3}_{\Lambda}\mathrm{H}$ structure is consistent with a weakly bound system.

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Hypernuclei are bound states of nucleons and hyperons that are particularly interesting because they can be used as experimental probes for the study of the hyperon-nucleon (Y-N) interaction. Searching for hypernuclei and exploring the Y-N interaction have been a source of fascination for nuclear physicists since the discovery of the first hypernuclei in 1953 [1]. In recent years, measurements of the hypertriton production and lifetime have stimulated an interesting debate in the high-energy physics community. The knowledge of the Y-N interaction has become more relevant recently due to its connection to the modeling of dense astrophysical objects like neutron stars [2,3]. Indeed, in the inner core of neutron stars the creation of hyperons is energetically favored compared to purely nucleonic matter [4]. The presence of hyperons as additional degrees of freedom leads to a considerable modification of the matter equation of state (EOS), prohibiting the formation of high-mass neutron stars. This is incompatible with the observation of neutron stars heavier than two solar masses [2,4], constituting what is referred to as the "hyperon puzzle." Many attempts were made to solve this puzzle, e.g., by introducing three-body forces leading to an additional repulsion that can counterbalance the large gravitational pressure and allow for larger star masses [5,6]. To constrain the parameter space of such models, a detailed knowledge of the Y-N interaction and of the three-body Y-N-N interaction is mandatory, including Λ, Σ, and Ξ hyperons. Numerous particle correlation analyses [7,8] directly contribute to the determination of such interactions. In a complementary approach, the lifetime and the binding energy of a hypernucleus reflect the strength of the Y-N interaction [9,10]. The current estimate of the separation energy of the Λ in the hypertriton is $\mathrm{B}_{\Lambda} = 181 \pm 48$ keV [11], which results in a rms radius (average distance of the Λ to the deuteron) of the order of 10 fm [12–15]. Lower values ($\sim$90 keV) of B_{Λ} are favored when fitting the correlation functions for protons and Λ baryons [16–18], therefore new measurements are required to understand this tension. The latest theoretical calculations predict a different degree of dependence of the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime on its binding energy. For pionless effective field theory (EFT) [19] based calculations, the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime is very close to the free Λ lifetime, with very little binding energy dependence for B_{Λ} values spanning from 0 to 0.5 MeV. On the other hand, in the χEFT approach [20], a stronger dependence on the binding energy is predicted for the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime being $\tau = (163 \pm 18)$ ps for $\mathrm{B}_{\Lambda} = 410$ keV and $\tau = (234 \pm 27)$ ps for $\mathrm{B}_{\Lambda} = 69$ keV. Previous measurements of the lifetime [21–26] and B_{Λ} [27] of ${}^{3}_{\Lambda}\mathrm{H}$ in heavy-ion collisions have still quite large uncertainties. In this Letter, new measurements with unprecedented precision of the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime and binding energy are presented to address the questions about its structure.

The presented results are based on data collected during the 2018 Pb-Pb LHC run at a center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The ALICE detector and its performance are described in detail in Refs. [28,29]. The data acquisition for Pb-Pb events is triggered by the V0A and V0C scintillation detectors [30], positioned at forward ($2.8 < \eta < 5.1$) and backward ($-3.7 < \eta < -1.7$) pseudorapidity, respectively. A coincidence of signals in both V0A and V0C is used as a minimum-bias trigger. In addition, two thresholds on the minimum amount of charge deposited on the V0 detector are employed to trigger on central and semicentral Pb-Pb collisions. A centrality estimator based on the V0 detector arrays [31] is used to select the 90% most central hadronic collisions. Events are further selected by allowing a 10 cm maximum displacement

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[*] Full author list given at the end of the article.

of the primary vertex along the beam axis from the nominal center of the experiment in order to benefit from the full acceptance of the detector. Finally, events with multiple reconstructed primary vertices are rejected to avoid ambiguous associations of $^{3}_{\Lambda}\mathrm{H}$ candidates to their production vertices. In total, about 300 million events are selected for this analysis.

In Pb-Pb collisions at the LHC, approximately the same number of $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\Lambda}\bar{\mathrm{H}}$ are expected to be produced. The $^{3}_{\Lambda}\mathrm{H}$ decays are detected via the charged two-body channel $^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-}$ (and the corresponding charge-conjugated particles for $^{3}_{\Lambda}\bar{\mathrm{H}}$). The decay products of the $^{3}_{\Lambda}\mathrm{H}$ are tracked with the Inner Tracking System [32] and the Time Projection Chamber (TPC) [33], which are positioned within a solenoid providing a homogeneous magnetic field of 0.5 T in the direction of the beam axis. Charged particles are tracked over the full azimuth and in the pseudorapidity interval $|\eta| < 0.8$. The specific energy loss of the decay products of $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\Lambda}\bar{\mathrm{H}}$ is also measured in the TPC, with a dE/dx resolution of about 5% [33,34]. The $n(\sigma_i^{\mathrm{TPC}})$ variable represents the particle identification (PID) response in the TPC expressed in terms of the deviation between the measured and the expected dE/dx for a particle species i, in units of the detector resolution σ. The expected dE/dx is computed with a parametrized Bethe-Bloch function [29]. Pion and $^{3}\mathrm{He}$ tracks within $\pm 5\sigma^{\mathrm{TPC}}$ are selected.

The identified $^{3}\mathrm{He}$ and π tracks are then used to reconstruct the $^{3}_{\Lambda}\mathrm{H}$ weak-decay topology with an algorithm similar to the one employed in previous analyses [23,25,35]. By combining the information on the decay kinematics and decay vertex, several selection variables are defined. Those used in the analysis are the following: the distance of closest approach both from the primary and the decay vertex and the $n(\sigma_i^{\mathrm{TPC}})$ of each daughter track; the number of clusters of the $^{3}\mathrm{He}$ track in the TPC; the reconstructed p_T of the $^{3}_{\Lambda}\mathrm{H}$; and $\cos(\theta_P)$, where θ_P is the angle between the total momentum vector of the decay daughters and the straight line connecting the primary and secondary vertices. These variables are combined as a gradient-boosted decision tree classifier (BDT) [36,37] that is trained on a dedicated Monte Carlo (MC) simulated event sample. The MC sample consists of $^{3}_{\Lambda}\mathrm{H}$ (decays) signals injected onto underlying Pb-Pb collisions simulated with the HIJING event generator [38]. The transverse momentum (p_T) distribution of the injected signals is given by the blast-wave [39] function, with parameters taken from simultaneous fits of the p_T distribution of light-flavored hadrons measured in Pb-Pb collisions [40]. Only candidates with $2 \leq p_T < 9$ GeV/c are considered. The particle transport through the detector material is done using GEANT4 [41], which simulates the interaction with the material and the weak decay of the $^{3}_{\Lambda}\mathrm{H}$. The BDT is a supervised learning algorithm that determines how to discriminate between two or more classes, in this case signal and background, by examining sets of examples called the training sets. In this analysis, the training sets comprise $^{3}_{\Lambda}\mathrm{H}$ signal candidates extracted from the MC sample and background candidates from paired like-sign $^{3}\mathrm{He}$ and π tracks from data. For each $^{3}_{\Lambda}\mathrm{H}$ candidate, the BDT combines topological and single-track variables to return a score, which is used to discriminate between signal or background. In particular, the most important variable employed by the BDT for the classification is the $\cos(\theta_P)$. Candidates with a BDT score higher than a given threshold are selected as signal. The threshold is defined to maximize the expected signal significance assuming a production yield as predicted by the thermal statistical hadronization model [13] for the $^{3}_{\Lambda}\mathrm{H}$ and the background rate observed when combining like-sign $^{3}\mathrm{He}$ and π pairs.

The $^{3}_{\Lambda}\mathrm{H}$ lifetime is extracted by analyzing the proper decay length spectrum shown in Fig. 1. The sample of $^{3}_{\Lambda}\bar{\mathrm{H}}$

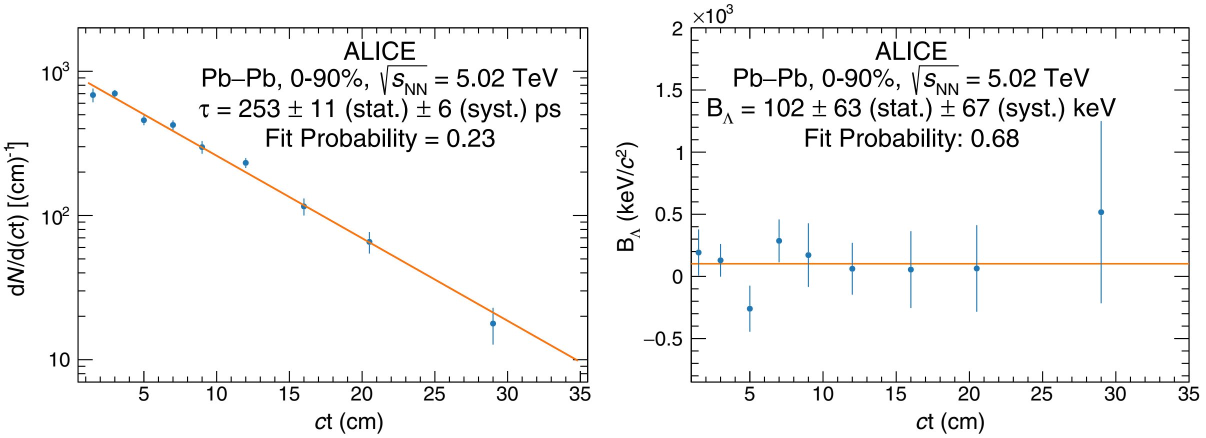

FIG. 1. Left: exponential decay spectrum as a function of the proper decay length for $^{3}_{\Lambda}\mathrm{H}$, the blue points represent the measured yield, while the orange line represents the best fit to the measurement. Right: B_Λ measurement as a function of the proper decay length. Only statistical uncertainties are shown; see the text for a description of the determination of the systematic uncertainties. The fit probability computed with a Pearson test is reported.

and ${}^{3}_{\Lambda}\mathrm{H}$ candidates is divided into nine $ct = ML/p$ intervals, where c is the speed of light, t is the proper time of the candidate, M is the mass of the candidate, L is the decay distance, and p is the reconstructed momentum. The BDT training and threshold optimization is repeated for each ct interval. The candidates that pass the BDT selection are used to populate the invariant-mass ($m = \sqrt{(E_\pi + E_{^3\mathrm{He}})^2 - |\vec{p}_\pi + \vec{p}_{^3\mathrm{He}}|^2}$) distributions, as shown in the Supplemental Material [42]. An unbinned maximum-likelihood fit is performed on the invariant-mass distribution using a kernel density estimator (KDE) function [43,44], constructed using the MC sample to describe the signal and a linear function to describe the background. The distributions obtained in the nine ct intervals can be found in the Supplemental Material [42]. The KDE is used to model the non-Gaussian behavior of the signal shape observed in the simulation by means of a superposition of Gaussian functions. The widths of the Gaussian functions are determined with an adaptive procedure that takes into account the local density of the signal in the MC sample. The yield in each ct interval is obtained from the fit to the invariant-mass spectrum. The fitted signal is corrected for the reconstruction and selection efficiency, and for the acceptance of the ALICE detector. While the interactions of the daughter particles are correctly reproduced by GEANT4 [45] and therefore naturally accounted in the efficiency determination, the interaction of the ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$ requires a dedicated treatment. According to Ref. [46], the expected absorption cross section of ${}^{3}_{\Lambda}\mathrm{H}$ due to the inelastic interactions in the ALICE detector material is about 1.5 times that of ${}^{3}\overline{\mathrm{He}}$ ($\sigma_{\mathrm{inel}}^{^3\overline{\mathrm{He}}}$). This value is used for simulating the passage of ${}^{3}_{\Lambda}\mathrm{H}$ in the detector and evaluating the effect on the reconstruction efficiency. Different corrections have been applied for ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$ according to their expected cross sections. The typical total efficiency (including acceptance, reconstruction, and selection) is around 15% while the absorption probability of ${}^{3}_{\Lambda}\mathrm{H}$ due to the inelastic interactions in the ALICE detector material is of the order of a few percent. The obtained spectrum is fitted with an exponential function as shown in the left panel of Fig. 1. The fit is performed by using the integral of the function in each bin to account for the variable widths of the ct intervals.

The major systematic uncertainties come from (1) the ${}^{3}_{\Lambda}\mathrm{H}$ identification and (2) the uncertainty on the ${}^{3}_{\Lambda}\mathrm{H}$ inelastic interactions in the detector. The total uncertainty is obtained as the quadratic sum of the individual contributions. The first, dominant contribution is computed by varying simultaneously the BDT selection efficiency ($\pm 10\%$), the background shape (linear, second order polynomial, and exponential), and the signal (KDE and double sided Crystal Ball [47]) fit functions in each ct interval. The systematic uncertainty is given by the rms of the distribution of lifetimes obtained from 5×10^4 different combinations and amounts to approximately 2%. The second contribution is evaluated by varying the ${}^{3}_{\Lambda}\mathrm{H}$ absorption cross section and evaluating the effect on the lifetime. The systematic uncertainty due to the assumption on the ${}^{3}_{\Lambda}\mathrm{H}$ absorption cross section is evaluated by employing different cross sections for the ${}^{3}_{\Lambda}\mathrm{H}$ from zero (no interaction) to $2\sigma_{\mathrm{inel}}^{^3\overline{\mathrm{He}}}$. For each variation the lifetime is recalculated, resulting in a systematic uncertainty of 1%.

The Λ separation energy B_Λ is obtained in each ct interval using the ${}^{3}_{\Lambda}\mathrm{H}$ mass ($\mu_{{}^{3}_{\Lambda}\mathrm{H}}$) extracted from the fit (see Supplemental Material [42]), the deuteron mass taken from CODATA [48], and the Λ mass taken from the PDG [49]. The reconstructed value of $\mu_{{}^{3}_{\Lambda}\mathrm{H}}$ is affected by the imperfect correction for the energy loss of the daughter particles in the ALICE material. This effect produces a shift that depends on the radial distance traveled by the ${}^{3}_{\Lambda}\mathrm{H}$ candidates before decaying, and it is evaluated by analyzing the MC simulations (δ_{MC}). The values of δ_{MC} as a function of the ct of the decay particles are shown in the Supplemental Material [42], and they span between -0.1 MeV and 0.8 MeV. To account for the possible mismatch between data and simulation, an additional data-driven correction is applied based on a dedicated precise measurement of the Λ mass. This represents an ideal test for the full analysis chain and for a potential data-simulation mismatch since the Λ mass is known with a precision of 6 keV [49] and its lifetime is compatible within 1σ with the ${}^{3}_{\Lambda}\mathrm{H}$ one. Hence, the Λ mass is computed with the same analysis procedure employed for the ${}^{3}_{\Lambda}\mathrm{H}$, and the positive shift obtained with respect to the PDG value ($\delta_\Lambda = 66$ keV) is used as our estimate of data-simulation mismatch and for correcting our value of $\mu_{{}^{3}_{\Lambda}\mathrm{H}}$. Finally, in each ct interval B_Λ is computed as $\mathrm{B}_\Lambda = m_d + m_\Lambda - (\mu_{{}^{3}_{\Lambda}\mathrm{H}} - \delta_{\mathrm{MC}} - \delta_\Lambda)$. The final B_Λ value and its statistical uncertainty are obtained from the average of the values measured in each ct interval (see Fig. 1, right) weighted on their statistical uncertainties.

The systematic uncertainties on B_Λ originate from (1) the ${}^{3}_{\Lambda}\mathrm{H}$ selection and the signal extraction, (2) the uncertainty on δ_Λ, and (3) the uncertainty on the ALICE material budget. The first contribution is computed using the same method as for the lifetime analysis and amounts to ± 29 keV. The uncertainty on δ_Λ takes into account a 60 keV shift observed by repeating the mass measurement for Λ and $\bar{\Lambda}$ with different magnetic field polarities. Finally, the systematic contribution due to the uncertainty of the ALICE material budget is computed by varying the material budget in the MC sample by its uncertainty and repeating the analysis. The B_Λ is recomputed for each variation, resulting in a systematic uncertainty of 8 keV. The systematic uncertainty is taken as the sum in quadrature of the three contributions. For the determination of the mean lifetime of the ${}^{3}_{\Lambda}\mathrm{H}$ and its B_Λ, the contribution from the knowledge of the magnetic

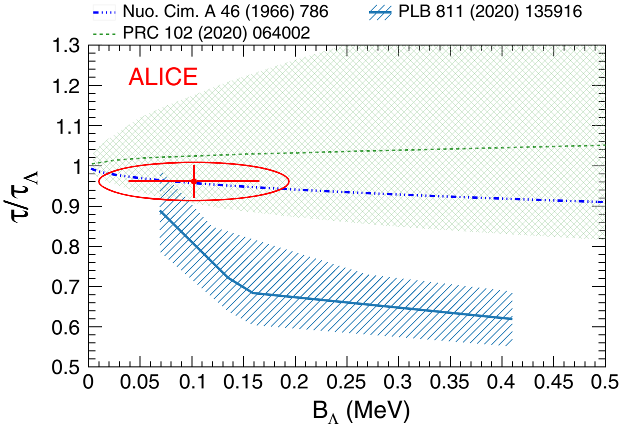

FIG. 2. The ${}^3_\Lambda$H lifetime relative to the free Λ lifetime as a function of the B_Λ for pionless EFT [19] (green), χEFT [20] (light blue), and the original π exchange calculations [50] (blue). The red point represents the measurement presented in this Letter with the statistical and total uncertainties depicted with lines and an ellipse, respectively.

field is considered by performing the analysis separately for positive and negative polarities of the solenoidal magnet. As the analyses with the two polarities returned results statistically compatible with each other, no further systematic uncertainty is added.

For both the lifetime and the B_Λ analyses, other potential sources of systematic uncertainty were tested, such as the input p_T and ct shape of ${}^3_\Lambda$H in the Monte Carlo sample, the BDT hyperparameters, the discrepancy between BDT and linear selections, and the ${}^3_\Lambda$H reconstruction algorithm, all resulting in a nonsignificant contribution.

The measurements for the ${}^3_\Lambda$H and ${}^3_\Lambda\bar{\text{H}}$ lifetime and B_Λ obtained with this analysis are

$$\tau = [253 \pm 11(\text{stat}) \pm 6(\text{syst})]\ \text{ps},$$
$$B_\Lambda = [102 \pm 63(\text{stat}) \pm 67(\text{syst})]\ \text{keV}.$$

As shown in Fig. 2, the measurements are in agreement with both the predictions from pionless EFT [19] and χEFT [20], while they severely restrict the phase space available for these theories and strongly confirm the weakly bound nature of ${}^3_\Lambda$H. Furthermore, the new measurement of the B_Λ is in agreement within 1σ with the binding energy value describing best the p-Λ correlations measured with the femtoscopy technique [17,18].

Finally, the relative differences between the ${}^3_\Lambda$H and ${}^3_\Lambda\bar{\text{H}}$ lifetimes and masses are measured, giving the values

$$\frac{\tau_{{}^3_\Lambda\text{H}} - \tau_{{}^3_\Lambda\bar{\text{H}}}}{\tau_{{}^3_\Lambda\text{H}}} = [3 \pm 7(\text{stat}) \pm 4(\text{syst})] \times 10^{-2},$$
$$\frac{m_{{}^3_\Lambda\text{H}} - m_{{}^3_\Lambda\bar{\text{H}}}}{m_{{}^3_\Lambda\text{H}}} = [5 \pm 5(\text{stat}) \pm 3(\text{syst})] \times 10^{-5},$$

which are consistent with zero and, therefore, with the CPT symmetry expectation. Note, in the mass difference measurement, the decay daughter masses are taken to be the same between particles and antiparticles.

In summary, the most precise measurements to date of the ${}^3_\Lambda$H lifetime and B_Λ, presented in this Letter, strongly support the loosely bound nature of ${}^3_\Lambda$H. The measured value perfectly agrees with the B_Λ that best fits the correlation

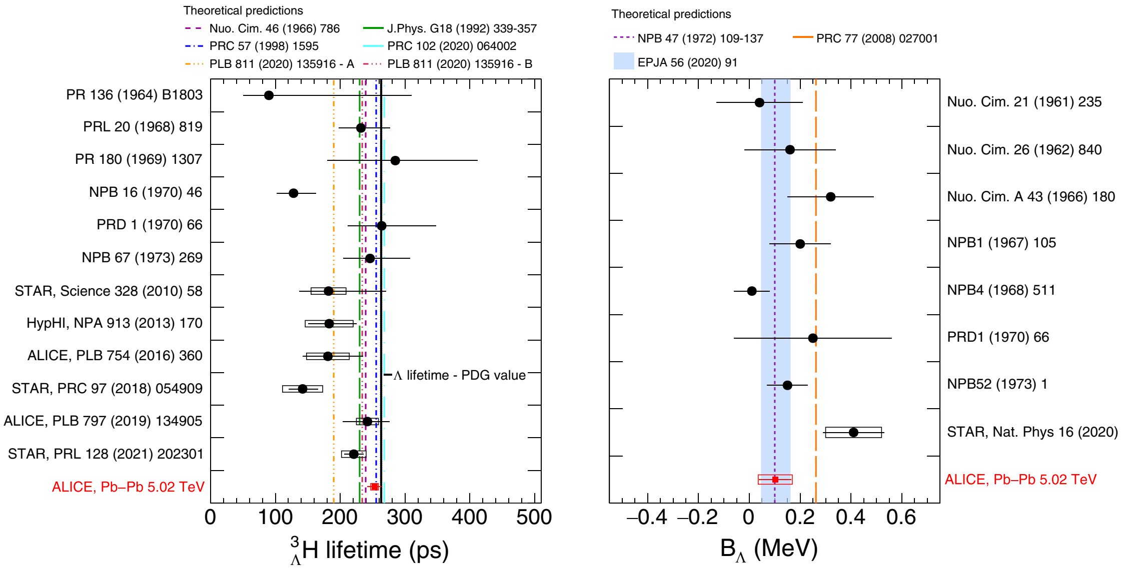

FIG. 3. Collection of the ${}^3_\Lambda$H lifetime (left) [21–26,51–56] and B_Λ (right) [27,55,57–62] measurements obtained with different experimental techniques. The horizontal lines and boxes are the statistical and systematic uncertainties, respectively. The dashed and dash-dotted lines are the corresponding theoretical predictions [10,17,19,20,50,63–65]. Two predictions are reported in [20]: prediction A assumes $B_\Lambda = 130$ keV, while prediction B assumes $B_\Lambda = 69$ keV.

functions for protons and Λ baryons within the current theoretical approaches [16–18].

Even though some local tensions among a few measurements of lifetime and B_Λ have been reported in the literature as the "hypertriton puzzle," when performing a global average of the historically available measurements (see Fig. 3 and the Mainz hypernuclear data database [11]), the probability of having such a set of measurements, computed with a Pearson test, is 23% for the lifetime and 57% for the B_Λ, hence no global tension is found. A remaining piece to be set for the complete understanding of the ${}^{3}_{\Lambda}\mathrm{H}$ structure is the measurement of branching ratios for the various decay channels [19]. The Run 3 of the LHC will make those measurements accessible with unprecedented precision.

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Correction: The last sentence in the caption of Fig. 3 contained an error and has been fixed.

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